Theoretical Spectral Models of T Dwarfs at Short Wavelengths and Their Comparison with Data

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ABSTRACT

We have generated new, self-consistent spectral and atmosphere models for the effective temperature range 600 K to 1300 K thought to encompass the known T dwarfs. For the first time, theoretical models are compared with a *family* of measured T dwarf spectra at wavelengths shortward of ∼1.0 micron. By defining spectral indices and standard colors in the optical and very near-infrared, we explore the theoretical systematics with T_{eff}, gravity, and metallicity. We conclude that the short-wavelength range is rich in diagnostics that complement those in the near-infrared now used for spectral subtyping. We also conclude that the wings of the Na D and K I (7700Å) resonance lines and aggressive rainout of heavy metals (with the resulting enhancement of the sodium and potassium abundances at altitude) are required to fit the new data shortward of 1.0 μm. Furthermore, we find that the water bands weaken with increasing gravity, that modest decreases in metallicity enhance the effect in the optical of the sodium and potassium lines, and that at low T_{eff}s, in a reversal of the normal pattern, optical spectra become bluer with further decreases in T_{eff}. Moreover, we conclude that T dwarf subtype is not a function of T_{eff} alone, but that it is a non-trivial function of gravity and metallicity as well. As do Marley et al. (2001), we see evidence in early T dwarf atmospheres of a residual effect of clouds. With cloudless models, we obtain spectral fits to the two late T dwarfs with known parallaxes, but a residual effect of clouds on the emergent spectra of even late T dwarfs can not yet be discounted. However, our focus is not on detailed fits to individual objects, but on the interpretation of the overall spectral and color trends of the entire class of T dwarfs, as seen at shorter wavelengths.

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1. Introduction

The discovery of Gliese 229B ushered in a new chapter in stellar astronomy by penetrating unambiguously below the main sequence edge (Nakajima et al. 1995; Oppenheimer et al. 1995). In Gliese 229B, absorption in the far infrared due to collision-induced absorption (CIA) by H_2 and the lack of absorption in the near infrared at the classic steam opacity windows together result in a redistribution of Gliese 229B's emergent flux from the mid- and far-IR to the Z ($\sim$1.05 μm), J ($\sim$1.25 μm), H ($\sim$1.6 μm), and K ($\sim$2.2 μm) bands in the near-infrared. These band fluxes exceed the corresponding black body values for a given T_{eff} by as much as two to three orders of magnitude. Given the importance of the near-infrared bands, it is only natural that they be used to help establish the associated new spectral types (Burgasser et al. 2001a; Geballe et al. 2002). Following on the heels of Gliese 229B, in the last few years more than twenty so-called "T" dwarfs (Strauss et al. 1999; Burgasser et al. 1999,2000a,2000c,2001a; Cuby et al. 1999; Tsvetanov et al. 2000; Leggett et al. 1999,2000; Geballe et al. 2002) and $\sim$200 so-called "L" dwarfs (Ruiz, Leggett, and Allard 1997; Delfosse et al. 1997; Kirkpatrick et al. 1999,2000; Martín et al. 1999) have been discovered (most by the 2MASS, SDSS, and DENIS surveys), introducing the first new "stellar" spectral types since the establishment and articulation of the original MKK system (Morgan, Keenan, and Kellman 1943; Morgan et al. 1992). This new progression of M→L→T from stars to brown dwarfs is one of the most exciting recent developments in "stellar" astronomy.

While the use of the near-infrared to characterize and type L and T dwarfs may be natural for low-temperature objects (most of which are substellar), this ignores their many interesting spectral features and unique behavior shortward of 1.0 micron, the classic realm of stellar classification. It has recently been shown that the potassium resonance doublet near 7700 Å and the sodium D line(s) around 5890 Å, along with their broad wings, dominate T dwarf spectra between 0.5 and 1.0 microns (Burrows, Marley, and Sharp 2000 (BMS); Tsuji, Ohnaka, and Aoki 1999; Liebert et al. 2000). It was also shown by BMS that the I-band magnitude of Gliese 229B measured by Golimowski et al. (1998) and by Matthews et al. (1996) is fully consistent with the potassium wing hypothesis. The resulting red/purple/magenta "visual" appearance and the diagnostic (and at times, counterintuitive; see §9) gravity, T_{eff}, and metallicity dependences of the short-wavelength spectra make the optical (loosely defined by the "CCD" cutoff) from $\sim$0.4 μm to $\sim$1.0 μm an intriguing subject of study and theoretical inquiry. Hence, in this paper we focus on the spectra of T dwarfs below 1.0 μm. We have calculated a new series of self-consistent spectra, colors, and spectral indices for theoretical brown dwarf atmospheres with T_{eff}s from 600 K to 1300 K. The low T_{eff}s of these models and the fact that they do not incorporate clouds/grains in their

atmospheres exclude the L dwarfs from this inquiry (Burrows et al. 2001; Ackerman and Marley 2001). However, although we concentrate here on the T dwarfs, we still find hints of the presence of clouds, particularly for the early Ts.

In §2, we summarize some of the recent T dwarf measurements shortward of 1.0 micron, which we interpret with the new theoretical models. In §3, we present a full suite of new theoretical spectra. These spectra will be used later in §7–§10 to extract information from the new T dwarf data at short wavelengths. Section 4 summarizes the major techniques, assumptions, and uncertainties in modeling of T dwarf spectra and includes an aside on the treatment of the alkali line profiles. In §5, we give example T/P profiles and representative plots of the $\tau_\lambda = 2/3$ temperature, $T_{2/3}$. Next, in §6 we define the spectral indices and colors we use throughout, particularly in §10. Note that §5 and §6 describe diagnostics by which one can better understand the observational trends. Then in §7, we provide representative fits to the spectra of Gliese 229B and Gliese 570D and continue in §8 with what can be learned with the new data at short wavelengths concerning the rainout of refractories (Burrows and Sharp 1999; Lodders 1999) and the line profiles of the alkali metals. After this, in §9 we describe the systematic dependences of the optical and near-infrared spectra on T_{eff}, gravity, and metallicity and in §10 we compare the theoretical spectral indices with those obtained using T dwarf spectra. Finally, in §11 we list several hints of the residual influence of clouds in early T dwarf atmospheres (see also Marley et al. 2001) and in §12 we summarize our general results and conclusions. Given the remaining ambiguities in both the gas-phase opacities (e.g., of methane, the alkali metals, water) and in the proper treatment of clouds and given the possible effects of non-equilibrium chemistry (Griffith and Yelle 1999,2000; Saumon et al. 2000; Lodders 1999), we are less interested in obtaining detailed fits than we are in the overall systematics of the class of T dwarfs. Hence, our focus in this paper is on the generic behavior at short wavelengths of the T dwarf *family* as a whole.

2.   The Observed T Dwarf Spectra Shortward of 1.0 μm

This is the first paper in which theoretical models and optical data for a large collection of T dwarfs, not just individual T dwarfs such as Gliese 229B (Marley et al. 1996; Allard et al. 1996; Tsuji et al. 1996,1999; Saumon et al. 2001) or Gliese 570D (Geballe et al. 2001), are compared. Table 1 itemizes 13 T dwarfs (and 2 late L dwarfs) with recently-obtained optical data. It lists objects in order of assigned spectral subtype (Kirkpatrick et al. 1999; Burgasser et al. 2001a) and provides the associated references and short-hand names we employ. More detailed discussions on the Keck LRIS (Oke et al. 1995) optical spectra of these T dwarfs and the associated signal-to-noise ratios can be found in Kirkpatrick et al. (2001) and Burgasser (2001a,b).

Figures 1 and 2 depict spectra for the objects listed in Table 1 (except for 2MASS-1237) from 0.6 μm to 1.0 μm. To facilitate intercomparison, these spectra have been normalized to a value of one at 1.0 μm. Normalization also serves to emphasize that we still don't know the parallaxes for most of these T dwarfs and, hence, can not assign absolute flux levels. The data shortward of

∼0.8 μm have a signal-to-noise ratio per pixel as low as ∼1 (Burgasser 2001b; Kirkpatrick et al. 2001). Therefore, below 0.8 μm we have used boxcar smoothing for the noisiest spectra to help discriminate between the relative flux levels of these T dwarfs in the ∼0.7 μm region.

As is clear from Figs. 1 and 2, the spectral slopes shortward of 1.0 μm cover a broad range of values and the spectra themselves fan out into a family that no doubt reflects variations in the underlying physical properties. Ignoring the two L dwarfs, the salient features are the water feature near 0.93 μm , the spectral slope in the 0.8 μm to 0.95 μm region, and the relative height of the bump between the KI resonance lines (∼7700Å) and the Na D lines (∼5890 Å). These features inform our choice of the spectral indices we define for this study (§6). Indeed, as was demonstrated by Liebert et al. (2000) with their optical spectrum of SDSS-1624 (T6), it is clear from Figs. 1 and 2 that the K I doublet at ∼7700Å and its wings dominate the region from 0.7 μm to 1.0 μm (see §3). Also, as is clearest for the early T dwarfs and 2MASS-0559 (T5, green in Fig. 1), absorption by the Na D lines is a natural explanation for the suppression of flux shortward of 0.7 μm . In principle, the equivalent widths of the Cs features at 8523 Å and 8946 Å and of the Rb features at 7802 Å and 7949 Å are additional diagnostics (Basri et al. 1999; Griffith and Yelle 2000). A useful index in this spectral region is the i$'$-z$'$ (Sloan AB; Fukugita et al. 1996) color, where i$'$ peaks in the region from ∼0.7 μm to ∼0.8 μm and z$'$ extends from approximately ∼0.8 μm to ∼1.0 μm .

The fact that the behavior of the spectra depicted in Figs. 1 and 2 is not completely monotonic with the infrared-determined spectral subtypes indicates to us that the T dwarf spectral subtypes are not determined solely by T_{eff} . Gravity and, perhaps, metallicity also play a role. In particular, the 2MASS-0559 (T5) (green curve in Fig. 1) spectrum shortward of 0.9 μm is "redder" than that of SDSS-1624 (T6) (blue curve in Fig. 1), despite the former's earlier spectral subtype. As we argue in §10, this implies that the surface gravity of SDSS-1624 (T6) is lower than that of 2MASS-0559 (T5). In addition, even though the spectral subtype of SDSS-1021 is T3, while that of SDSS-1254 is T2, the relative flux level of SDSS-1021 is generally above (at both 0.73 μm and 0.83 μm) that of SDSS-1254. Since in §3 and §9 we demonstrate in the likely T_{eff} range of SDSS-1021 and SDSS-1254 that decreases in T_{eff} and increases in gravity increase the redness of the spectrum shortward of 0.9 μm , we conclude that the gravity (and presumably the mass) of SDSS-1021 is lower than that of SDSS-1254. Though T_{eff} is the major determinant, a sufficiently large gravity difference can reverse the apparent dependence of subtype on changes in T_{eff} .

The optical data depicted in Figs. 1 and 2 are state-of-the-art, but, in particular for the later T dwarfs and shortward of 0.8 μm , they are of fairly low resolution. Nevertheless, these spectra can help guide us in this exploration of the dependence of optical spectra on T dwarf physical properties and in discerning the range of gravities and T_{eff}s represented by the objects in Table 1. The near absence of parallaxes is an impediment to detailed fits, as is the noise in the observed spectra at shorter optical wavelengths. However, the optical colors and spectral indices (§6 and §10) that can be calculated for the growing list of T dwarfs with measured spectra shortward of 1.0 μm still provide useful physical diagnostics with which our suite of theoretical models can be used to determine the possible range of their T_{eff}s , gravities, and metallicities.

3. Theoretical Brown Dwarf Spectra from 1300 K to 600 K

As a prelude to the discussions in §7–§10, we present a collection of new theoretical spectra that span the T dwarf regime. Figure 3 portrays the absolute flux ($\mathcal{F}_\nu$) in milliJanskys versus wavelength from 0.4 μm to 1.5 μm for solar-metallicity models for the two gravities and the full range of T_{eff}s (see §4). The higher curves in Fig. 3 are for models with the higher T_{eff}s . Prominent are the Na D and K I resonance doublets at ∼5890 Å and ∼7700 Å, the water bands around 0.93 μm , 1.15 μm , and 1.4 μm , the Cs I lines at 8523 Å and 8946 Å, the Li I line at 6708 Å, the Rb I lines at 7802 Å and 7949 Å, and (for the hottest models) the TiO and VO features near ∼0.45 μm and 0.9→1.05 μm . At 1.2432/1.2522 μm the K I doublet is seen for T_{eff}s at 700 K and above. It was assumed in these models that clouds/grains/dust that may form at depth nevertheless have no effect on an object's T/P profile, nor on its spectrum. As we argue in §11, this may not be true for the earliest T dwarfs. In determining molecular abundances, unless otherwise stated we employed the rainout prescription for the refractory silicates described in Burrows and Sharp (1999). As explained in that reference and in Burrows, Marley, and Sharp (2000), rainout depletes the atmospheres of the refractory elements Ca, Al, Mg, Fe, and Si. This affects the abundance profiles of not only the nascent alkali metals, but TiO, VO, FeH, and CrH. In particular, rainout suppresses the formation of alkali feldspars and enables atomic Na and K to survive to lower temperatures and pressures, at which point they form $Na_2S(c)$ and $KCl(c)$ (Lodders 1999). As a consequence, their influence on the emergent spectrum in the "optical" between 0.5 μm and 1.1 μm is enhanced. Rainout also restricts the range of lower temperatures and pressures where TiO, VO, Fe(l,c), CrH, and FeH can be found. However, since the CrH opacities are soon to be updated significantly, FeH and CrH bands were not incorporated into this model set and we defer a discussion of their role to a later work (see also §4).

The normalized observed spectra shortward of 1.0 μm were presented in Figs. 1 and 2. The corresponding normalized theoretical spectra at solar-metallicity and for gravities of 10^5 cm s^{-2} and $10^{5.5}$ cm s^{-2} are displayed in Fig. 4. A comparison of Figs. 1, 2, and 4 is illuminating and reveals that the theoretical family nicely spans the observations. Furthermore, the general overall spectral shapes, particularly from 0.8 μm to 0.9 μm , are reproduced. We compare these model spectra with data in §7-§9. However, we first discuss some of the major uncertainties in the models and a variety of physical diagnostics that are useful in interpreting measurements.

4. Model Assumptions, Techniques, and Uncertainties

To construct new atmosphere/spectral models of brown dwarfs, we employ the complete linearization/accelerated-Λ-iteration method of Hubeny and Lanz (1995), molecular and atomic opacities as described in Burrows et al. (2001), and the equation of state of Saumon, Chabrier, and Van Horn (1995). We explore both rainout, using the prescription of Burrows and Sharp (1999) (see also Lodders 1999), and non-rainout composition assumptions, though when not explicitly stated

rainout has been incorporated. The T/P profiles at depth obtained using the Lodders (1999) and the Burrows and Sharp (1999) rainout prescriptions are the same (all else being equal) to better than 2% (M. Marley, private communication).

The depletion of refractories into silicate clouds is an intrinsically non-equilibrium and dynamical process. Hence, any prescription that purports to address this can do so only crudely. Fortunately, it is the clouds at depth into which settle/rain the refractory elements that would have been in the upper atmospheres that are the most problematically handled; the upper atmospheric depletions of Mg, Si, Fe, Al, and Ca themselves and the resultant metal-depleted molecular compositions are better handled, yielding compositions that are probably good to better than 10%. Since our modeling is focussed on T dwarfs in which clouds play no central role (however, see §11), our rainout prescriptions are as good as current practice allows. However, at the higher T_{eff}s in the L dwarf regime, the actual physics of clouds (and their particle sizes, spatial extent, optical properties, and degree of patchiness) assumes a greater importance. Furthermore, the possible effects of non-equilibrium chemistry and rapid transport of spectroscopically-active species may also be important (Lodders 1999; Griffith and Yelle 1999,2000; Saumon et al. 2000). In particular, though CO and NH_3 have no strong bands short of 1.0 micron and play only a very minor role in setting the T/P profile of a T dwarf, the suggestion that their abundances may be out of equilibrium due to dynamic convective transport deserves further attention (Saumon et al. 2000; Noll, Geballe, and Marley 1997). Quite obviously, no current prescription for cloud opacities or for dynamic transport and their effects on emergent spectra can be beyond reproach or improvement. In this paper, given our focus on T dwarfs we ignore both.

Our models are produced using the opacity sampling technique to arrive at converged and consistent temperature/pressure profiles, from which higher-resolution spectra are then calculated for a given spectral interval. For the T/P profile calculation, no more than 2000 wavelengths are needed, which range from 0.4 μm to 300 μm. Each model was converged in temperature and flux to better than 0.1% in typically a few minutes on a standard workstation. The speed of our code is a direct consequence of the complete linearization approach. Marley et al. (2001) and Burrows et al. (1997) use the k-coefficient method with the equivalent of ∼800 wavelengths. Similar to the ODF method, their implementation avoids its major pitfall by combining the abundance-weighted opacities of all the relevant molecules and atoms before creating the distribution function that is at the heart of the ODF approach. We use a mixing-length prescription to handle convection, with a mixing-length parameter of 1.0. Marley et al. (2001) flatten the entropy gradient in convective regions. Saumon et al. (2000) use the T/P profiles generated by Marley, as in Marley et al. (2001). Allard et al. (2001) use mixing-length theory, with a mixing-length parameter of 1.0. At low T_{eff}s, the actual mixing length parameter is irrelevant; changing the mixing-length parameter from 0.5 to 2.0 changes the T/P profile by no more than ∼20 K. However, above T_{eff} ∼1500 K, the actual value of this parameter is an issue of modest interest. Nevertheless, the theoretical T/P profiles in grainless atmospheres below T_{eff} = 1500 K are similar, differing by no more than 10% (usually less) at atmospheric levels from 800 K to 2000 K (cf. this work; Marley, unpublished; Allard et al.

2001).

For the spectra we display here, 5000 wavelengths, logarithmically spaced from 0.4 μm to 1.5 μm, were used and then the spectrum was boxcar-smoothed to an effective resolution, R ($\lambda/\Delta\lambda$), of 1000 at each wavelength. Models were generated with T_{eff}s from 600 K to 1300 K, in steps of 100K (plus at a few extra T_{eff}s , when needed), at two gravities ($g = 10^5$ cm s^{-2} and $10^{5.5}$ cm s^{-2}), and for three metallicities (Z) (0.3×solar, solar, and 2.0×solar). The Anders and Grevesse (1989) abundance data were used to represent/define the solar pattern. This T_{eff} -gravity-Z parameter set was chosen to allow us to span the model space in which it is reasonable to assume the newly-discovered T dwarfs reside, as well as to gauge the systematic behavior of the observables with T_{eff} , gravity, and metallicity.

The brown dwarf radii (R) assumed were derived from the analytic formula found in Burrows et al. (2001) and Marley et al. (1996):

$$R \;\; = \;\; 6.7 \times 10^4 \mathrm{km} \Big(\frac{10^5}{g}\Big)^{0.18} \Big(\frac{T_{eff}}{10^3}\Big)^{0.11} ,$$

where g is in cm s^{-2} and T_{eff} is in Kelvin. This procedure is not perfectly consistent, since the evolutionary models upon which this equation for the radius is based incorporate slightly different atmosphere models as boundary conditions. Nevertheless, the error in the radius is small ($\lesssim 10\%$) and the derived colors and spectral indices are independent of radius.

The major differences between theoretical models arise from the different opacity databases employed. For substellar dwarfs, the major gas-phase opacities are due to H_2O, H_2, CH_4, CO, NH_3, the neutral alkali metals, TiO, VO, FeH, and CrH. A subsidiary role is played by PH_3, MgH, CaOH, CaH, SiO, and H_2S. Importantly, the *equilibrium* abundances of the dominant molecules (in particular, H_2O, H_2, CH_4, CO, N_2, and NH_3) are easily calculated (Burrows and Sharp 1999). Most researchers use the same H_2 (Borysow and Frommhold 1990; Zheng and Borysow 1995; Borysow, Jørgensen, and Zheng 1997) and H_2O (Partridge and Schwenke 1997) opacities. We calculate our TiO and VO opacities using Plez (1998,1999) and Jørgensen (1997), including the effects of isotope shifts, and believe them to be state-of-the-art. As stated in §3, we omit FeH and CrH from this T dwarf model set. Their omission affects predominantly L dwarfs in the spectral regions around 0.86 μm and 0.99 μm (FeH, the Wing-Ford band), but does not change to any significant degree T-dwarf T/P profiles, nor the vast majority of the spectrum where FeH/CrH features do not contribute. Note that, as do most researchers in this field (Saumon et al. 2000; Marley et al. 2001; Allard et al. 2001), we currently use the 52-million line subset of the 308-million line Partridge and Schwenke (1997) water database. Though recently questions have been raised concerning its accuracy in some wavelength regimes (Jones et al. 2002), the Partridge and Schwenke compilation remains the best available.

Methane opacities are an important wildcard, with the "hot bands" and the red side of the H photometric band being the most problematic (Burrows et al. 2001). However, apart from a minor band near 0.89 μm, methane plays only a very modest role in "optical" T dwarf spectra,

though its effects in the infrared help to define the T dwarfs and the L→T transition (Burgasser et al. 1999). The methane feature that has the most effect on a T/P profile is the strong ν_3 band at 3.3 μm, but its opacity seems to be well in hand. Not unexpectedly, most researchers use much the same methane opacity data (cf. Burrows et al. 2001; Saumon et al. 2000; Marley et al. 2001). Nevertheless, it is in the different implementations of the extant line lists and opacity databases, in the different collisional broadening prescriptions, and in the inaccuracies in these various databases that one is likely to find the origin of most of the differences between the various theoretical models (Burrows et al. 1997; Allard et al. 2001; Tsuji et al. 1999; Saumon et al 2000; Geballe et al. 2001; Marley et al. 2001) and between theory and data. However, the alkali lines and their wing profiles are a special case to which we now turn.

4.1. An Aside on the Assumed Shapes of the Alkali Line Wings

As emphasized in Burrows, Marley, and Sharp (2000), it is not strictly correct to use Lorentzian profiles for the Na D ($\sim$5890 Å) and K I ($\sim$7700 Å) doublets in their far wings, as we do for this paper and as is the standard practice in most stellar atmospheres work. In fact, the dominance of these doublets is a central feature of brown-dwarf/T-dwarf spectra and colors at wavelengths from 0.4 μm through 1.0 μm. While the line core behavior and oscillator strengths for these transitions are well in hand (Piskunov et al. 1995), there remain ambiguities in the treatment of these lines at large detunings ($\Delta\lambda$) and the as-yet-unknown shapes of their wings will have a bearing on the viability of spectral fits. For this study, we have used the default Lorentzian out to a transition wavelength redward of the line cores (7700 Å for Na D and 9800 Å for the K I doublet), after which we allow the strength to decay as a Gaussian in wavelength with a width of $0.075\times\lambda_{\rm central}$. The latter merely results in a smooth cutoff at a large detuning, but is otherwise arbitrary. This prescription for the alkali wings is different from that suggested by Burrows, Marley, and Sharp (2000) because in this paper we want to make only minimal alterations to the standard Lorentzian until better estimates of the wing shapes are available. The BMS prescription has an ad hoc parameter q whose value affects the far wing line shape and introduces an "effective" cutoff, but is in fact unconstrained. A choice of $q = 0.6$ for K and $q = 0.2$ for Na provides as good a fit to T dwarf spectra as the simpler prescription we employ here, given the noise in the optical data (Liebert et al. 2000). However, the use of a BMS q parameter implies a certain functional form that is not motivated by the proper physical chemistry, only by the need for a cutoff (§8).

Though the general overall spectral shapes seen in Fig. 4, particularly from 0.8 μm to 0.9 μm, are reproduced (Liebert et al. 2000) with either the BMS or our modified Lorentzian prescriptions, there are two features that are problematic in the comparision of Figs. 1, 2, and 4. One is that the theoretical peak between the K I and Na D troughs is shifted by $\sim$0.02 μm to shorter wavelengths than the observed average. This could easily be a consequence of the all-too-simple alkali line profile algorithms used. The other is that for the earlier T dwarfs the K I trough at 7700 Å is a bit narrower than derived using either the BMS or the current theory. Both prescriptions yield equally

discrepant spectral shapes, though the fractional deviations in the flux densities or "equivalent widths" derived using either prescription are at most a few tens of percent. It should be noted that the prescriptions for the alkali line shapes used in the literature have included a pure Lorentzian with a sharp cutoff at an arbitrary wavelength at a large detuning (Allard et al. 2001), a pure Lorentzian with a sharp cutoff at an arbitrary wavelength at a small detuning (Tsuji et al. 1999), and the Burrows, Marley, and Sharp (2000) prescription (Marley et al. 2001; Saumon et al. 2000; Geballe et al. 2001). Frequently, however, the alkali-line-shape prescription employed in a paper is unexplained and sometimes the Na/K alkali metals have been omitted (Griffith, Yelle, and Marley 1998).

The data shortward of 0.8 μm are indeed noisy, so this might be a major factor in any discrepancies between our theoretical spectra and observation, but as the comparison of Figs. 1, 2, and 4 nevetheless demonstrates, the remaining $\sim$10-50% ambiguity in the flux densities is much smaller than the factors of $\sim$2–10 deviations previously seen in the literature shortward of 0.8 μm (cf. Tsuji et al. 1999). Hence, our current approach to the Na/K alkali-line shapes is as reasonable as any, but the reader should bear in mind the need for significant further improvement.

5.   T/P Profiles and the "$\tau_\lambda = 2/3$" Temperature

The dependence of the theoretical spectra on T_{eff}, gravity, and metallicity is a major focus of this paper. Effects such as the general reddening in the optical with decreasing T_{eff} (at a given gravity), which reverses at lower effective temperatures (particularly noticeable in Fig. 4 around 0.75 μm), will be discussed in §9. To facilitate that discussion, we present here representative model temperature/pressure profiles in Fig. 5 and representative plots of the $T_{2/3}$ temperature versus wavelength in Fig. 6. $T_{2/3}$ is defined in this paper as the temperature level in the brown dwarf atmosphere at which the total optical depth is 2/3. Roughly, it is the temperature of the layer to which one is probing when measuring a spectrum at the corresponding wavelength and is a measure of the depth to which an observed spectrum is allowing us to peer (see also Saumon et al. 2000, their Figure 6). Fig. 5 can be used to gauge the dependence on T_{eff}, gravity , and metallicity of the optical depth above a given temperature level in an atmosphere. As Fig. 5 suggests, lower-metallicity models have higher pressures at a given temperature and higher-T_{eff} models have lower pressures at a given temperature. Moreover, as would be expected from hydrostatic equilibrium, higher-gravity models have higher pressures at a given temperature.

$T_{2/3}$ is the "decoupling" temperature at a given wavelength, or the wavelength-dependent temperature level to which one probes an atmosphere by measuring its spectrum. Fig. 6 indicates that shortward of 1.0 μm, higher gravities result in slightly lower $T_{2/3}$s and higher T_{eff}s always result in higher $T_{2/3}$s. In addition, Fig. 6 shows that in the Z band ($\sim$1.05 μm), one is probing to $\sim$1500-1600 K for the 1100 K models and that in the J band ($\sim$1.25 μm), one is probing to $\sim$1400-1500 K, for the same models. Note that below the Na D line at $\sim$5890 Å, $T_{2/3}$ for the sample models is rising to between 1200 and 1600 K, while at the centers of the strong Na D and

K I resonance doublets, $T_{2/3}$ is near 800 K.

6. Definitions of Color Indices

Color-color diagrams are traditional tools used to determine the physical properties of stars. In addition, non-traditional, but diagnostic, spectral indices (ratios of flux levels or flux averages at different wavelengths) can perform the same function (Burgasser et al. 2000b; Burgasser 2001b; Geballe et al. 2002; Tokunaga and Kobayashi 1999). Such indices are very useful for encapsulating and describing trends in $T_{\rm eff}$, gravity, and metallicity and in isolating one class of objects from another. This is especially true when spectral data are noisy, when subtle changes in plotted spectra are difficult to discern by eye, or when distances are not known (as is currently the case for the majority of T dwarfs). Hence, we have calculated a set of spectral indices and colors that highlight various features of the family of T dwarf spectra, both theoretical and observed, and use them to derive physical facts about the T dwarfs listed in Table 1, as well as about the spectral class as a whole.

The indices we have defined are:

$$X97 = \log_{10}(F_\lambda(0.90 - 0.91\mu{\rm m})/F_\lambda(0.72 - 0.73\mu{\rm m})),$$

$$X98 = \log_{10}(F_\lambda(0.90 - 0.91\mu{\rm m})/F_\lambda(0.855 - 0.86\mu{\rm m})),$$

$$X23 = \log_{10}(F_\lambda(0.92 - 0.925\mu{\rm m})/F_\lambda(0.928 - 0.945\mu{\rm m})),$$

and

$$X126.105 = \log_{10}(F_\lambda(1.26\mu{\rm m})/F_\lambda(1.05\mu{\rm m})).$$

Note that F_λ (not F_ν) is used, that a range of wavelengths implies an average in the indicated wavelength range, and that the indices do not have a prefactor of 2.5. These indices were chosen to highlight important features in T dwarf spectra at shorter wavelengths. Both X97 and X98 were defined to avoid the water feature at $\sim$0.93 μm. X97 is a measure of the relative flux in the spectral bump between the Na D and K I (7700 Å) lines and the region around 0.9 μm and captures the effect of rainout. X98 is a measure of the slope between 0.8 μm and 0.9 μm and, hence, is a measure of the shape of the red wing of the K I line at 7700Å. X23 is a measure of the depth of the water feature near 0.93 μm and reflects the influences of H_2O abundance, gravity, and the residual effect of silicate clouds. X126.105 is a measure of the ratio of the fluxes at 1.26 μm and 1.05 μm, near the traditional J and Z bands at the prominent peaks in T dwarf spectra (see Fig. 3). Our indices short of 1.0 μm are similar to those employed by Burgasser et al. (2001b) and Geballe et al. (2002), but are a bit better tuned to capture physical effects, as opposed to observational trends. However, almost any of the "optical" indices recently defined by those measuring L and T dwarfs

could have sufficed. (Tokunaga and Kobayashi (1999) do not define indices short of 1.0 μm, the spectral region on which we have focussed in this paper.)

We also use the the colors i$'$ - z$'$ and $J - K$, where the former is in the Sloan AB system and the latter is in the Bessell (or Cousins) system (Bessell and Brett 1988). Importantly, the choice of system or index for the purpose of deriving trends is arbitrary. We chose Bessell for the $J - K$ color to connect with the traditional color system in light of the continuing confusion in the use of UKIRT, Ks, and 2MASS filters; there is as yet no uniformity from telescope to telescope in the use of near-infrared filter sets. Hence, our colors are just like spectral indices (e.g., X97 ...) and those calculated and discussed here should be viewed as such. Our colors are derived from spectra, not photometry, and they are used to discover trends, not to compare with standard-star-calibrated values. Nevertheless, our i$'$ - z$'$ and $J - K$ (Bessell) colors are as good as any, given the differences between the underlying spectra of calibration standards and T dwarfs and given the accuracy of the flux calibration for the data (Burgasser et al. 2000a). Note that $J - K$ has been included in this paper, despite our emphasis on the optical, to make at least one tie-in with the spectral range now being used to define the T dwarf spectral subtypes.

In Table 2, we provide these indices and colors for T_{eff}s from 600 K to 1300 K, gravities of 10^5 cm s^{-2} and $10^{5.5}$ cm s^{-2}, and metallicities of 0.3×solar, solar, and 2.0×solar, where solar is defined by Anders and Grevesse (1989). We include "no-rainout" models at 900 K and the two gravities and the observed T dwarfs listed in Table 1. Table 2 summarizes all the basic trends (on which we focus in §10). We use these indices in the following sections to facilitate the diagnosis of the observed spectral trends.

7. Fits to Gliese 229B and Gliese 570D Spectra

That our prescription for the alkali line shapes has some merit is demonstrated in Fig. 7, where solar-metallicity spectral fits for the two T dwarfs, Gliese 229B and Gliese 570D, for which there are published parallaxes (Perryman et al. 1997; 5.8 and 5.9 parsecs, respectively) are presented. For Gliese 570D (as for the other T dwarfs in this paper), ours is the first paper to compare data with theory below 0.8 μm. (For Gliese 229B, there are no spectral data as yet below 0.85 μm, only R and I band photometry.) The spectra portrayed in Fig. 7 are given in absolute flux units. The shape of the spectrum from 1.0 μm to 1.1 μm, the slope of the spectra around 0.8 to 0.9 μm, the Gliese 229B WFPC2 R band measurement (Golimowski et al 1998), the flux level at $\sim$0.7 μm for Gliese 570D, and the i$'$-z$'$ color for Gliese 570D are all reproduced. As Fig. 7 indicates, our theoretical fluxes for both Gliese 229B and Gliese 570D (which span more than three orders of magnitude) are good to 10–30%, though the noise below 0.8 μm is problematic. Geballe et al. (2001) do not study Gliese 570D shortward of 0.8 μm. However, they obtain comparably good fits above 0.8 μm, though we reproduce the shapes and magnitudes in the Z and J bands more closely. Focussed on Gliese 229B and NH$_3$, Saumon et al. (2000) do not discuss spectra shortward of 1.0 μm. Marley et al. (2001) do not compare theoretical spectra with observational data. In their Gliese 229B

campaign, Griffith, Marley, and Yelle (1998) and Griffith and Yelle (1999) do not include the Na and K alkali lines in their opacity database. Instead, they posit the existence at altitude of a cloud of red grains whose imaginary index of refraction has a more extreme dependence on wavelength than that of Titan tholins, red phorphorus, or polyacetylenes (Noy, Podolak, and Bar-Nun 1981; Khare and Sagan 1984). In their important Gliese 229B study, Tsuji et al. (1999) conclude that a combination of silicate dust with the K I doublet at 7700 Å can explain its spectrum shortward of 1.0 μm. However, as is still the standard practice in stellar atmospheres work, Tsuji et al. truncated the alkali lines at very small detunings, which necessitated the introduction of another component to explain the spectrum. As did BMS, we find that including the wings of the potassium doublet obviates the need for another component to explain the sharp declivity shortward of 1.0 μm in T dwarf spectra in general (Fig. 1 and 2) and in Gliese 229B's spectrum in particular.

As Fig. 7 indicates, the relative flux ratios in the Z and J bands are well-modeled. In contrast, the best-fit model of Gliese 229B by Tsuji et al. (1999) in the Z and J bands is off by a factor of 2–3, reflecting the need to cutoff the alkali metal wings as discussed in §4.1 and §8. Importantly, the corresponding no-rainout spectra below 0.8 μm (not shown) (Allard et al. 2001) are generically off by a factor greater than 5 (§8). Slightly more precise fits can in fact be achieved by adjustments in T_{eff}, metallicity, and gravity. However, our purpose here is not to obtain the ultimate fit, but to verify our general approach and to extract the essential conclusions about the class of T dwarfs as a whole using spectra at short wavelengths.

Nevertheless, the depths of the water features near 0.93 μm, 1.15 μm and 1.4 μm (not shown) are not fit well. Leakage in the spectrometer of light from adjacent peaks into the troughs might explain the effect at 1.4 μm, and perhaps a fraction of the effect at 1.15 μm, but these are major discrepancies that may point to a residuum of dust in the atmosphere (Tsuji et al 1999; Saumon et al. 2000) or to problems with the water opacity database used (Partridge and Schwenke 1997). The models of all groups fail to explain these water troughs (Saumon et al. 2000; Marley et al. 2001; Allard et al. 2001). Lowering the metallicity enough, particularly for a majority of the T dwarfs in Table 1 which all manifest this problem, would not seem to be a viable option generically (Allard et al. 2001; however, see Griffith and Yelle 1999). Furthermore, a low-enough metallicity that would solve the problem at 0.93 μm would also shift the $J - K$ magnitudes away from the observed values for the T dwarfs (Burgasser et al. 2001a) by as much as -0.5 magnitudes at 900 K. (However, a lower metallicity may be implicated for 2MASS-0937; see §10.)

A T_{eff} for Gliese 570D of $\sim$750 K at a low gravity of 10^5 cm s^{-2} (mass $\sim$30 M_J) is similar to that derived in Geballe et al. (2001), but at their low end. Equally good solar-metallicity fits to Gliese 570D can be found from $\sim$750 K to $\sim$840 K, where the corresponding gravities range from 10^5 cm s^{-2} to $\sim$10$^{5.4}$ cm s^{-2}. Our T_{eff} range for Gliese 570D is a bit more conservative than that of Geballe et al. (2001) due to the fact that we have not imposed an age constraint. However, as demonstrated in Fig. 7 for Gliese 229B, at the current level of observational precision it is only a trajectory in T_{eff}-gravity space (given roughly by $T_{eff}/g^{0.2} = $ const.) that can be constrained. Gliese 229B could have a T_{eff} near 780 K and a gravity near $10^{4.5}$ cm s^{-2} (mass $\gtrsim$15 M_J). What

is shown in Fig. 7 are just representative fits to the Gliese 229B and Gliese 570D data. Solar-metallicity models of Gliese 229B that fit these spectra include those with T_{eff}s from 780 K to 950 K (higher would imply a higher gravity than is realistic for brown dwarfs). Very subsolar-metallicity models for Gliese 229B would compromise the acceptable fits in $J - K$.

Without parallaxes, we prefer not to provide spectral fits for the other T dwarfs in Table 1. It is not that fits can't be obtained. That they can should be clear from Figs. 3 and 4 and from Table 2. Rather, the problem is that too many models can be found to fit, and T_{eff} and gravity are only loosely constrained. Nevertheless, our models and the indices discussed in §10 yield for all but the early T dwarfs a T_{eff} range of 900±150 K. With parallaxes, we should be able to tighten this constraint and determine the T_{eff}/g trajectory (and core entropy; Burrows, Marley, and Sharp 2000) for each observed T dwarf. However, at this stage, we don't want to claim more than is prudent.

8.   Conclusions Concerning Alkali Metal Line Profiles and Rainout

There are a few conclusions of a qualitative nature, in particular concerning the truncation of the resonance lines of Na and K and the seeming necessity of rainout, that deserve special mention. Figure 8 demonstrates many of these with a collection of representative theoretical model spectra at $T_{eff} = 900$ K and solar metallicity from 0.4 μm to 1.5 μm. All the spectral models have T/P profiles that are consistently derived for the opacities and abundance prescriptions used. The solid red line depicts the [900 K/10^5 cm s^{-2}] model and the solid blue line the [900 K/$10^{5.5}$ cm s^{-2}] model. The black line portrays a model with $g = 10^{5.5}$ cm s^{-2}, but uses Lorentzian line profiles without cutoffs for the Na D and K I (7700 Å) lines. In addition, this spectrum does not incorporate the rainout of Ti and V species, and, hence, leaves them suspended in the atmosphere in strict chemical equilibrium. The dashed blue line is a [900 K/$10^{5.5}$ cm s^{-2}] model, but one that does not incorporate a prescription for the rainout of the silicates and the consequent survival of Na and K to lower temperatures and pressures in the atmosphere. The spectrum of 2MASS-0559 (T5) is included on Fig. 8 in green and is the absolute flux spectrum under the assumption that its distance is 10 parsecs.

That unmodified Lorentzians produce spectra that do not fit is demonstrated in Fig. 8 by the relative positions of the black line (Lorentzian model) and the solid blue line. The latter spectrum in the Z (∼1.05 μm) and J (∼1.25 μm) bands is much closer to the data shown in Fig. 7 and to those obtained for the objects in Table 1 by Burgasser (2001b); the truncated models do not decapitate the Z and J bands by as much as an order of magnitude in the way that the untruncated Lorentzian does. As mentioned in §7, the absence of such a cutoff is the reason for the discrepancy by a factor of 2 to 3 in the Tsuji, Ohnaka, and Aoki (1999) model for Gliese 229B in the Z and J bands. The difference at $T_{eff} = 900$ K and $g = 10^{5.5}$ cm s^{-2} between our standard model result and that with untruncated Lorentzians is ∼1.2 magnitudes in i'-z'; the X98 and X97 indices are similarly incorrect (Table 2).

Note that, since Na is $\sim$20 times more abundant than K, it is Na that would account for most of this anomalous suppression beyond 1.0 μm, despite the greater spectral distance of the Na D line. One concludes from Fig. 8 that the true line profiles must be truncated and are not strictly Lorentzians.

As is clear from Fig. 8, the no-rainout (dashed blue) and rainout (solid blue) spectra differ by 0.5-1.0 dex from one another, particularly at 0.7 μm between the dominating Na D and K I resonance doublets. A comparison of these curves with the new T dwarf spectra provided in Figs. 1 and 2 leads to the strong conclusion that the no-rainout models do not fit the new optical data. This is clear confirmation of the BMS prediction (see their Figures 2 and 3) for the "entire" family of T dwarfs, not just for SDSS-1624 (Liebert et al. 2000), and is consistent with the Marley et al. (2001) Figure 3. Geballe et al. (2001) came to a similar conclusion for Gliese 570D vis à vis rainout, but did not have data nor theory shortward of 0.8 μm. Given the ambiguities in the alkali line profiles near 1.0 μm, spectra from 0.8 μm to 1.0 μm can not be used to draw clear conclusions about the occurrence of rainout; it is only with the new data at shorter wavelengths (< 0.8 μm) that one can distinguish unambiguously between the effects of rainout and of the unknown alkali line profile shapes, given the well-known oscillator strengths.

As Table 2 indicates, i$'$ - z$'$ for the no-rainout models is as much as 1.0-1.5 magnitudes discrepant. The indices X98 and X97 tell a similar story. Without rainout, the "redness" of the optical spectra and the large flux contrast between the Z peak and the bump at 0.7-0.75 μm can not be reproduced. Rainout leads to an enhancement in the abundance of atomic Na and K at lower temperatures (and lower pressures) in the atmosphere and to greater absorption shortward of 0.9 μm. A comparison on Fig. 8 of the spectrum of 2MASS-0559 (T5) with the no-rainout/rainout theoretical curves serves to emphasize this point (2MASS-0559 is here merely representative of the T dwarfs listed in Table 1). Hence, we have in the new T dwarf spectra at short wavelengths evidence for the influence of cloud formation at depth and element depletion (Si, Mg, Al) at altitude (Burrows and Sharp 1999; Burrows, Marley, and Sharp 2000; Lodders 1999), leading to the suppression of alkali feldspar production at higher temperatures near $\sim$1400 K and the consequent persistence of atomic Na and K to lower atmospheric temperatures. In particular, the fit displayed in Fig. 7 for Gliese 570 D and the approximate fit to the Gliese 229B datum in the R band do not seem possible with any no-rainout models.

As a test, for the Lorentzian model portrayed on Fig. 8 we suppressed the effects of rainout on the TiO and VO abundances, thereby enhancing the abundances of those molecules at altitude. As this T_{eff} = 900 K model demonstrates, around 0.45 μm (near the B band) TiO features would be visible, even for a model with such a low T_{eff}. This is a consequence of the low gaseous opacities at the shortest wavelengths. The high $T_{2/3}$s (Fig. 6) in this wavelength range say the same thing; at short wavelengths one is probing deeply. If such features are not seen (and this we suspect), it would be another indication of rainout. Moreover, cloud veiling could also be implicated. Hence, observations at wavelengths even shorter than the Na D line(s) can provide information concerning the deep atmosphere.

9. The Systematic Dependence of T Dwarf Spectra on T_{eff}, Gravity, and Metallicity

From the spectra presented in Figs. 3, 4, and 8, the representative T/P profiles and $T_{2/3}$s shown in Figs. 5 and 6, and the indices and colors tabulated in Table 2, we can determine the general theoretical trends for T dwarf spectra with T_{eff}, gravity, and metallicity.

9.1. Systematics with T_{eff}

Just as Fig. 5 and all previous calculations indicate, as the effective temperature decreases for a given gravity the pressure in the atmosphere at a given temperature increases. This implies that the column depth in gm cm^{-2} to a given temperature level increases with decreasing T_{eff} (in hydrostatic equilibrium, column depth $= P/g$). Hence, for a ubiquitous species such as water, the $\tau = 2/3$ surface that roughly determines the position of the "photosphere" (on average, or at a given wavelength) is at progressively lower temperatures with decreasing T_{eff} (see Fig. 6). The result is that $T_{2/3}$ in the water absorption troughs near 0.93 μm, and between the Z, J, and K bands (for instance), as well as those at the emission peaks themselves, decreases. However, since the near-IR is not on the Rayleigh-Jeans tail, these decreases in $T_{2/3}$ lead to an increase in the flux contrast from peak to valley, as well as to an overall decrease in the fluxes. Hence, the water troughs deepen with decreasing T_{eff} and, as Table 2 demonstrates, $J - K$ gets *bluer* with decreasing T_{eff} (Burrows et al. 1997; Allard et al. 2001). Roughly, this may be what is seen for the T dwarfs in the near IR (Burgasser et al. 2001a) and in Figs. 1 and 2. At the higher T_{eff}s (in the Ls and early to mid Ts), the systematics with decreasing T_{eff} described above for water can also be seen in the spectral region shortward of 1.0 micron dominated by the alkali metal lines and wings. In addition, increasing pressure with decreasing T_{eff} leads to greater pressure-broadening, enhancing the influence of the alkali metal wings. Both effects lead to a *reddening* of the spectrum below $\sim$1.0 μm with decreasing T_{eff} which has been identified in previous theoretical explorations (e.g., BMS; Marley et al. 2001; Allard et al. 2001).

However, the Na and K abundances are very small below a certain temperature (1050 K to 850 K, depending on element and pressure). Since there is such a "top" to the atomic alkali region, as T_{eff} decreases further at low T_{eff}s the region containing Na and K atoms becomes more and more buried. The result is a gradual diminution of the role of the Na and K lines from 0.4 to 1.0 μm and a consequent "bluing" of the spectrum below $\sim$1.0 μm. This effect below 1.0 μm was predicted by BMS; we now quantify it and in Fig. 4, which shows the incipient closing of the K I absorption trough at 7700 Å and the slight bluing of the optical spectrum at low T_{eff}s. The gravity- and metallicity-dependent reversal of the indices X97, X98, and i$'$-z$'$ at low T_{eff}s is captured in Table 2. Recently, this prediction for the low T_{eff} behavior of T dwarfs, as seen in i$'$-z$'$, has been verified by Marley et al. (2001). The turnaround with decreasing T_{eff} in the behavior of these spectral indices and of the i$'$-z$'$ color is even more clearly portrayed in Figs. 10, 12, and 13 (discussed in §10). For the i$'$-z$'$ color, T_{eff} for this transition ranges from $\sim$700 K to $\sim$800 K. In this T_{eff} range, both i$'$-z$'$

and the overall spectral shape shortward of 1.0 micron are weak functions of T_{eff} .

9.2. Systematics with Gravity

A T dwarf with a T_{eff} of $\lesssim 1000$ K and a gravity of $10^{5.5}$ cm s^{-2} has a mass near 70 M_{J} (and an age $\gtrsim 10^{9.7}$ years). One with a gravity of 10^5 cm s^{-2} has a mass near 35 M_{J}. As we go down in gravity to $10^{4.5}$ cm s^{-2}, we are exploring masses just above 15 M_{J}. The observed T dwarfs may possibly span this entire range. Figure 5 shows that as the gravity increases the pressure at a given temperature in the atmosphere increases as well. What this figure does not show is that the column depth of material actually decreases with increasing gravity. This means that for a given T_{eff} , the depths of the water troughs and the contrasts between the emission peaks and these troughs actually *decrease* with increasing gravity. In particular, we discover that the relative depth of the water feature near 0.93 μm (measured by X23) decreases with increasing gravity. This is opposite to the effect of decreasing T_{eff} . One consequence is that any indices constructed from the contrasts between peak and water trough are not a one-parameter family in T_{eff} alone. Hence, we find that the effect of decreasing T_{eff} can be compensated by an increase in gravity. Importantly, as Table 2 demonstrates, increasing the gravity by 0.5 dex has the same effect on $J - K$ as decreasing T_{eff} by 100-200 K. Hence, given the current method of T dwarf spectral subtyping in the near-IR (Burgasser et al. 2001a; Geballe et al. 2002), effective temperature alone can not be construed to imply subtype. At a given T_{eff} , lowering the gravity can lead to a later subtype. Moreover, a later subtype does not necessarily imply a lower T_{eff} .

As Table 2 indicates, $J - K$ gets bluer with increasing gravity. This is predominantly a consequence of the pressure dependence of the CIA opacity of H_2 at 2.2 μm . Shortward of 1.0 micron, at higher T_{eff}s increasing gravity reddens the i′-z′ color and increases (steepens) the X97 and X98 indices. However, at lower T_{eff}s an increase in gravity leads to a slight reversal and i′-z′ becomes bluer. This newly-quantified behavior can be seen in Fig. 12 (§10) and Table 2 and is a consequence of the same systematics in the atmospheric profiles (Fig. 5) discussed earlier that are responsible for the reversal in the T_{eff} dependence of the optical colors and slopes at lower T_{eff}s .

9.3. Systematics with Metallicity

Figure 9 portrays the metallicity dependence of T dwarf spectra from 0.4 μm to 1.5 μm , for a single representative T_{eff} of 900 K and a gravity of $10^{5.5}$ cm s^{-2}. Metallicities at 0.3, 1.0, and 2.0 times solar are compared. Shortward of 0.9 μm , we find that the lower-metallicity model is redder and the higher-metallicity model is bluer than the solar model. This newly-quantified effect may seem backwards, since one might have expected a lower metallicity to weaken the effects of the alkali metals. However, as the metallicity is lowered, the abundances of the other metals (such as oxygen in the form of water) are also lowered, leading to a more transparent atmosphere. As a

result, one is peering more deeply into the atmosphere to higher pressures. This is clearly apparent in the relative positions on Fig. 5 of the red (low-metallicity) lines. At higher pressures, the Na D and K I resonance lines at $\sim$5890 Å and $\sim$7700 Å are stronger. Hence, i$'$-z$'$ reddens with decreasing metallicity. This is quite similar to what happens in subdwarf M stars. Overall, the solar and 2.0$\times$solar models are very similar shortward of 1.0 μm. Unless the metallicity is significantly subsolar (Griffith and Yelle 1999), the metallicity dependence of T dwarf spectra in the optical is weak (except perhaps shortward of 0.6 μm). Note that our lower-metallicity model has a more rounded Z band peak. Such a shape is not in evidence in the T dwarf data.

The differences in the near-IR at H and K are more pronounced, with lower-metallicity models being generically more blue in $J - K$ and $H - K$. For instance, from 600 to 1300 K, the differences between the solar-metallicity and the 0.3$\times$solar-metallicity models vary from 0.1 to 0.5 magnitudes in $J - K$ (cf. Table 2 and Fig. 12). The higher pressures in the low-metallicity atmospheres increase the CIA opacity and suppress the K band flux. We find that decreasing the metallicity by a factor of three has a greater effect on the K band than increasing the gravity by the same factor. This behavior with metallicity requires that if Gliese 229B has a low metallicity (Griffith and Yelle 1999) it must also have a low gravity. High-gravity models for Gliese 229B can not simultaneously be low-metallicity (Allard et al. 2001). It would be very useful for the determination of the physical parameters of the T dwarf Gliese 229B to obtain its spectrum from $\sim$0.6 μm to 0.8 μm and its X97 and i$'$-z$'$ indices (consistently calibrated).

10. Index and Color Comparisons

Figures 10, 11, 12, and 13 are "color-color" diagrams that summarize the numerical data in Table 2. The upper-case letters on the figures represent the positions in these index plots of the measured T dwarfs. The letter that corresponds to a given T dwarf is indicated in Table 2 and in the figure caption to Fig. 10. Errors of $\gtrsim$0.1 dex in the X indices and $\sim$0.25 in i$'$-z$'$ and $J - K$ (Bessell/Cousins) colors have been suppressed on these figures to avoid further clutter and to allow the basic collective gestalt to emerge. The lines on the plots are families as a function of T_{eff} at given gravities and metallicities. Each point represents an T_{eff} from 600 K to 1300 K, in steps of 100 K. The basic success of the models is clear from the correspondence between the regions occupied by the observed T dwarfs and where the theory points reside. In principle, a comparison of the observed positions on these plots with those for the theoretical models would allow one to determine T_{eff}, gravity, and metallicity. However, the errors in the indices and the overlaps of the model families make such a determination a bit less straightforward. In fact, such errors make it difficult to determine T_{eff} and gravity for most of the T dwarfs listed in Table 1 to better than $\pm$150 K in T_{eff} and 0.25 dex in gravity. Fits to most of the measured spectra can be obtained, but without parallaxes and given the remaining errors in the data they tell us very little we can use. Hence, we prefer not to provide specific object-by-object T_{eff} and gravity estimates, unless parallaxes are available or the object is an outlier in its spectrum or indices. Nevertheless, from

Table 2, Fig. 4, the new optical data, and our theoretical models we can infer that the T_{eff}s of the listed T dwarfs, except for the three early Ts, are 900±150 K. The corresponding gravity range could in principle span our model set from $10^{4.5}$ cm s^{-2} to $10^{5.5}$ cm s^{-2}. Note that values for the T_{eff}s of the early T dwarfs are approximately bracketed by 1100 K and 1300 K (see Table 2, Figs. 10, 11, 12, and 13). Parallaxes would enable a determination of the possible T_{eff} /g line for each object (as obtained in §7 for Gliese 229B) and are eagerly awaited.

From Fig. 10, we see that our theory successfully provides the correct general overall X97/X98 slope and distinguishes the L dwarf region from the T dwarf region. Furthermore, it demonstrates that if the observed early T dwarfs (green) are not generically low-gravity objects (dashed), that the T dwarf edge has an effective temperature near 1300 K. (If these early T dwarfs were low-gravity objects, the T dwarf edge would be even lower in T_{eff} .) This L/T boundary temperature is in contrast with the ∼1600 K suggested by Basri et al. (1999). For higher gravity, SDSS-1254 (T2,D) would have a T_{eff} near 1200 K. However, despite the inclusion of rainout, the models are still displaced downward by ∼0.2 dex in X97. (Note that the non-rainout models [cf. Table 2] would be displaced downward in X97 by a further ∼0.5 dex and to the left in X98 by ∼0.2 dex!)

The fact that 2MASS-0937 (T6p,I), Gl 570D (T8,N), and 2MASS-0415 (T8,O) are outliers is consistent with their lower T_{eff} , higher gravity, or lower metallicity. In particular, 2MASS-0937, due to its high X97 (and i′-z′; see Fig. 11) and to the fact that in the near-IR it was typed by Burgasser et al. (2001a) as an earlier subtype than the other two, seems clearly to have either a higher gravity or a lower metallicity than the average T dwarf observed to date (Burgasser et al. 2001a). The lower-metallicity solution is slightly favored when one looks at the other index figures and makes a consensus judgment. Furthermore, the Z-band spectrum of 2MASS-0937 (Burgasser et al. 2001a) is a bit more rounded than average, reminiscent of the behavior of the low-metallicity model depicted in Fig. 9. We do not draw any conclusions from the lonely position of 2MASS-1237 (K) on this figure and on Figs. 11 and 12 due to the noisiness of its spectrum between the Na D line and the K I line at 7700 Å. Better data are clearly needed.

Figure 11 demonstrates once again that our basic theoretical treatment shortward of 1.0 micron is not far wrong. We also see that the T_{eff}s of modest- to high-gravity models of the early T dwarfs must be ≤1300 K and that 2MASS-0937 (I) is best fit with a low-metallicity model, though not definitively so. However, the proximity of the model lines, their overlap, and the errors in the data together make it difficult to draw detailed conclusions concerning the "central" T dwarfs.

Figure 12 is a color-color diagram that demonstrates the non-monotonic behavior of i′-z′ with T_{eff} (§9) and the outlier status of 2MASS-0937. It also makes the case that the early T dwarfs are not fit well in the near infrared by this grainless model set. No doubt, part of the problem lies with the incomplete methane opacity database in the H and K bands, notably the absence of the "hot" bands of methane. However, this can not account for the full discrepancy. The theoretical models are too blue in $J-K$ and the best explanation for this is the influence of residual dust/grains/clouds even in the early T dwarfs SDSS-0837 (T1,C), SDSS-1254 (T2,D), and SDSS-1021 (T3,E). The

possible presence of grains is also suggested in Fig. 13, which portrays both the behavior of X98 with X23 (H_2O jump) and the non-monotonic behavior with T_{eff} discussed previously. Figure 13 shows that the depth of the water feature near 0.93 μm is not well reproduced by the models, unless many of the observed T dwarfs are of low metallicity (Griffith and Yelle 1999,2000). We surmise that extra opacity due to dust may be shallowing the water trough near 0.93 μm by 0.1 to 0.15 dex. Such dust may also be contributing to the general reddening shortward of 1.0 micron (Tsuji, Ohnaka, and Aoki 1999), still dominated by the wings of the K I (7700 Å) doublet.

The index figures and Table 2 allow one to draw some qualitative conclusions concerning specific T dwarfs. As indicated in Fig. 7, Gliese 229B can be fit by a low-g/low-T_{eff} or a high-g/high-T_{eff} model. However, its value of X23 (J on Fig. 13, one of the highest for the observed T dwarfs) implies that the low-gravity solution is preferred. It is probable from their values of i'-z', X97, and X23 that SDSS-1624's gravity is lower than that of 2MASS-0559. Furthermore, a direct comparision of SDSS-1624's spectrum with that of Gliese 229B leads one to conclude that its gravity is greater than that of Gliese 229B. In addition, a comparison of the i'-z', X98, and X97 indices for SDSS-1021 (T3) and SDSS-1254 (T2) leads one to conclude that SDSS-1021 has the lower gravity. This is also the conclusion arrived at in §2 directly from the spectra. SDSS-1021 could also have a higher T_{eff} .

11. Hints of Clouds

The discussion in §8 points to a quite interesting fact. At T_{eff}s near the early edge of the T dwarf family ($\sim$1300 K), $T_{2/3}$ in the Z and J bands reaches 1700-1800 K for atmospheres without the opacity effects of clouds. This suggests that the silicate/iron clouds expected to reside above 1500-1700 K might significantly affect the shape and strength of the J and Z emission peaks, even at such low T_{eff}s . A very similar conclusion was reached by Marley et al. (2001). This is not unreasonable, since the L to T transition is thought to coincide with the settling to depth of the clouds that dominate the L dwarf spectral type (Ackerman and Marley 2001; Burrows et al. 2001). The spectra of the early T dwarfs should show the residual influence of such clouds. Indeed, as we argue in §10, the (i'-z')/($J-K$) color-color diagram suggests that clouds are required to fit the early T dwarfs SDSS-0837 (T1), SDSS-1254 (T2), and SDSS-1021 (T3). As the $T_{2/3}$ temperature argument suggests, it is in the Z and J bands where the effects of clouds are primarily expected. Our spectral models at $\sim$1300 K (Fig. 3) manifest TiO and VO features in these bands because we have not included the effects of clouds. Clouds should not only mute the effects of TiO and VO on the Z and J bands of the $T_{eff} = $ 1200/1300 K models in Fig. 3, but should also help reduce the contrast between the emission peaks at Z, J, and K and the water troughs at 1.15 μm and 1.4 μm (Jones and Tsuji 1997). Furthermore, because the subordinate K I absorptions at 1.2432/1.2522 μm are from a thermally-excited state, they are formed only at high atmospheric temperatures. Coincidently, they reside in the middle of the J band where one is probing higher temperatures, as indicated by the higher $T_{2/3}$s there (Fig. 6). However, the strengths we derive

for these subordinate lines (see Fig. 3) are generally greater than observed (McLean et al. 2000; Saumon et al. 2000). This too may point to a mitigating role of veiling clouds/dust/grains. Hence, there are numerous spectral regions that speak to the potential influence of clouds on T dwarf spectra.

However, there remains a puzzle that may not be so easily explained by dust. The classic Li feature at 6708 Å is included in our model set and can be seen on the curves in Fig. 3. Observations (Kirkpatrick et al. 1999) suggest that the strength of this feature peaks in the mid-L spectral range and then drops monotonically. Currently, there is little indication of this line in the observed late L dwarfs, nor in the T dwarfs. However, in both our rainout and no-rainout (unpublished) models the Li line survives to below $T_{eff} = 600$ K. Allard et al. (2001) also obtain this feature at low T_{eff}s and Pavlenko (2001) has an extensive theoretical discussion concerning its formation in late L dwarfs. Since lithium burning in objects that currently have T dwarf T_{eff}s occurs only for a narrow range of masses and gravities ($> 2.5 \times 10^5$ cm s^{-2}), nuclear burning seems to be excluded as a generic explanation. Chemistry would be the natural culprit, but both the Burrows and Sharp (1999) and Lodders (1999) rainout prescriptions and the no-rainout prescription (true equilibrium) give qualitatively the same result. Since atomic Li should exist in abundance to temperatures around 1300 K (Lodders 1999) and should trail off below that and since $T_{2/3}$s around 6700 Å are 1000 K to 1350 K for T_{eff}s from 700 to 1300 K (see Fig. 6 for 700→1100 K), there is no obvious reason the 6708 Å Li line should disappear before the L/T boundary. Therefore, we suspect there is an interesting story to be told about real brown dwarf atmospheres in the resolution of this Li-line problem.

12.   Conclusions

We have generated spectral models for the temperature range 600 K to 1300 K thought to encompass the T dwarfs. Comparing these models with the new T dwarf data shortward of 1.0 micron, we find that the models can explain in qualitative and semi-quantitative fashion, the new observations and their systematic trends. Furthermore, we demonstrate that untruncated Lorentzian line profiles for the Na D and K I (7700 Å) resonance doublets are disfavored, that the atmospheric abundances of sodium and potassium have indeed been enhanced by the rainout of silicates (BMS; Lodders 1999), that water bands weaken with increasing gravity, that modest decreases in metallicity enhance the effect of the alkali lines in the optical, and that at low T_{eff}s the behavior of the optical spectra with T_{eff} reverses and becomes bluer with further decreases in T_{eff} (as predicted by BMS). Moreover, we find that the upper edge of the T dwarf T_{eff} range is near ∼1300 K.

We determine that the optical range is rich in diagnostics that are complementary to those in the near-infrared now used for spectroscopic classification. An important conclusion is that the T dwarf subtype is not a function of T_{eff} alone; subtype is also a non-trivial function of gravity and metallicity. Even if the range of metallicities represented by the known T dwarfs is small, gravity

will play an important role in the near-IR and shortward of 1.0 micron in determining spectral shape, colors, and spectral subtype.

From the shallowness of the water feature near 0.93 μm, from the weaker than predicted K I features in the J band, from the failure of the models to fit the $J - K$ colors of the early T dwarfs, and from the presence in the hotter models of TiO and VO features in the Z and J bands (not seen in the observations of the earlier T dwarfs), we find evidence of residual dust/grains/clouds in early T dwarf atmospheres. A similar conclusion was recently reached by Marley et al. (2001). The L dwarfs are known to be dominated by clouds (Burrows et al. 2001, and references therein), and the transition from the L dwarfs to the T dwarfs is predominantly due to the depletion and rainout of heavy metals (Ackerman and Marley 2001; Burrows and Sharp 1999; Marley et al. 1996; Allard et al. 1996). However, the continuing effect of clouds in the early T dwarfs seems to be indicated by the data. Clouds in T dwarf atmospheres do not explain the redness of the spectrum shortward of 1.0 μm (though they might contribute to it); this is mostly explained by the K I line at 7700 Å and its wing (Burrows, Marley, and Sharp 2000). However, the L and T transition is not as abrupt as earlier inferred by the sharp swing to the blue of $J - K$. One can still see deeply into the atmosphere, even for low T_{eff}, into regions occupied by silicate (and other?) clouds. The opacity spectrum of clouds is much more continuous and featureless than that of gas. As a consequence, the influence of clouds is manifest by broad shape changes in the optical and near-IR spectra and by the suppression of gas-phase spectral features, not by specific and distinct spectral features, until one gets to $\sim$10 μm and the classical silicate band appears. Certainly, good models of the particle size spectrum, spatial extent, and composition of the grains or droplets are required to reproduce the measured spectra of the early T dwarfs in detail. The later T dwarfs are easier to fit, but the residual effect of clouds at depth on the emergent spectra can not yet be discounted.

The T dwarfs are all brown dwarfs and the number of such substellar objects known to astronomy is growing fast. Their spectra hold the key to their physical characterization and shortward of 1.0 micron these spectra have great diagnostic potential. We have attempted to make only a preliminary stab at comparing the new data at short wavelengths with theory and look forward to the creation of better opacity databases and cloud models, more precise spectral measurements, and the measurement of parallaxes that together will enable the final, detailed determination of the masses, gravities, T_{eff}s, and compositions of the objects that inhabit this fascinating new spectral class.

REFERENCES

Ackermann, A. and Marley, M.S. 2001, ApJ, 556, 872

Allard, F., Hauschildt, P.H., Baraffe, I. & Chabrier, G. 1996, ApJ, 465, L123

Allard, F., Hauschildt, P.H., Alexander, D.R., Tamanai, A., and Schweitzer, A. 2001, ApJin press.

Anders, E. and Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197

Basri, G. et al. 2000, ApJ, 538, 363

Bessell, M.S., and Brett, J. M. 1988, PASP, 100, 1134

Borysow, A. and Frommhold, L. 1990, ApJ, 348, L41

Borysow, A., Jørgensen, U.G., and Zheng, C. 1997, A&A, 324, 185

Burgasser, A.J., et al. 1999, ApJ, 522, L65

Burgasser, A.J., et al. 2000a, ApJ, 531, L57

Burgasser, A.J., Kirkpatrick, J. D., Reid, I. N., Liebert, J., Gizis, J. E., & Brown, M. E. 2000b, AJ, 120, 473

Burgasser, A.J., et al. 2000c, AJ, 120, 1100

Burgasser, A.J., et al. 2001a, ApJ, 563, in press

Burgasser, A.J. 2001b, Ph.D. thesis, California Institute of Technology

Burrows, A., Marley M., Hubbard, W.B. Lunine, J.I., Guillot, T., Saumon, D. Freedman, R., Sudarsky, D. and Sharp, C.M. 1997, ApJ, 491, 856

Burrows, A. and Sharp, C.M. 1999, ApJ, 512, 843

Burrows, A., Marley, M. S., and Sharp, C. M. 2000, ApJ, 531, 438

Burrows, A., Hubbard, W.B., Lunine, J.I., and Liebert, J. 2001, Rev. Mod. Phys., 73, 719

Cuby, J.G., Saracco, P., Moorwood, A.F.M., D'Odorico, S., Lidman, C., Comerón, F., and Spyromilio, J. 1999, A&A, 349, L41

Delfosse, X., Tinney, C.G., Forveille, T., Epchtein, N., Bertin, E., Borsenberger, J., Copet, E., De Batz, B., Fouqué, P., Kimeswenger, S., Le Bertre, T., Lacombe, F., Rouan, D., and Tiphène, D. 1997, Astron. Astrophys. , 327, L25

Fan, X., et al. 2000, AJ, 119, 928

Fukugita, M. et al. 1996, AJ, 111, 1748

Geballe, T.R., Saumon, D., Leggett, S.K., Knapp, G.R., Marley, M.S., and Lodders, K. 2001, ApJ, 556, 373

Geballe, T.R. et al. 2002, ApJ, 563, in press

Golimowski, D. A., et al. 1998, AJ, 115, 2579

Griffith, C.A., Yelle, R.V., and Marley, M.S. 1998, Science, 282, 2063

Griffith, C.A. and Yelle, R.V. 1999, ApJ, 519, L85

Griffith, C.A. and Yelle, R.V. 2000, ApJ, 532, L59

Hubeny, I. and Lanz, T. 1995, ApJ, 439, 875

Jones, H.R.A. and Tsuji, T. 1997, ApJ, 480, L39

Jones, H.R.A., Pavlenko, Y., Viti, S., and Tennyson, J. 2002, Mon. Not. Roy. Astron. Soc., in press.

Jørgensen, U.G., 1997, in *Molecules in Astrophysics: Probes and Processes*, ed. E.F. van Dishoeck, (Kluwer, IAU Symp. 178), pp. 441-456

Khare, B.N. and Sagan, C. 1984, Icarus, 60, 127

Kirkpatrick, J.D., Reid, I.N., Liebert, J., Cutri, R.M., Nelson, B., Beichman, C.A., Dahn, C.C., Monet, D.G., Gizis, J., and Skrutskie, M.F. 1999, ApJ, 519, 802

Kirkpatrick, J. D., Reid, I. N., Liebert, J., Gizis, J. E., Burgasser, A. J., Monet, D. G., Dahn, C. C., Nelson, B., & Williams, R. J. 2000, AJ, 120, 447

Kirkpatrick, J.D., et al. 2001, submitted to ApJ

Leggett, S. K., Toomey, D. W., Geballe, T. R., and Brown, R. H. 1999, ApJ, 517, L139

Leggett, S. K., et al. 2000, ApJ, 536, L35

Liebert, J., Reid, I. N., Burrows, A., Burgasser, A. J., Kirkpatrick, J. D., & Gizis, J. E. 2000, ApJ, 533, L155

Lodders, K. 1999, ApJ, 519, 793

Marley, M.S., Saumon, D., Guillot, T., Freedman, R.S., Hubbard, W.B., Burrows, A. & Lunine, J.I. 1996, Science, 272, 1919

Marley, M.S., Seager, S., Saumon, D., Lodders, K., Ackerman, A.S., and Freedman, R. 2001, ApJ, in press (astro-ph/0105438).

Martín, E. L., Delfosse, X., Basri, G., Goldman, B., Forveille, T., & Zapatero Osorio, M. R. 1999, AJ, 118, 2466

Matthews, K., Nakajima, T., Kulkarni, S.R., & Oppenheimer, B.R. 1996, AJ, 112, 1678

McLean, I., et al. 2000, ApJ, 533, L45

Morgan, W. W., Keenan, P.C., and Kellman, E. 1943, An Atlas of Stellar Spectra, with an Outline of Spectral Classification. (Chicago: Univ. Chicago Press)

Morgan, D.H., Tritton, S.B., Savage, A., Hartley, M., and Cannon, R.D. 1992, in Digitised Optical Sky Surveys, ed. H.T. MacGillivray and E.B. Thomson (Dordrecht: Boston), p. 11

Nakajima, T., Oppenheimer, B.R., Kulkarni, S.R., Golimowski, D.A., Matthews, K. and Durrance, S.T. 1995, Nature, 378, 463

Noll, K., Geballe, T.R., & Marley, M.S. 1997, ApJ, 489, 87

Noy, M., Podolak, M., and Bar-Nun, A. 1981, J. Geophys. Research, 86, 11985

Oke, J.B. et al. 1995, PASP, 107, 375

Oppenheimer, B.R., Kulkarni, S.R., Matthews, K., and Nakajima, T. 1995, Science, 270, 1478

Partridge, H. and Schwenke, D.W. 1997, J. Chem. Phys., 106, 4618

Pavlenko, Ya.V., 2001, Astronomy Reports, 45, 144

Perryman, M.A.C. 1997, Astron. Astrophys. , 323, L49

Piskunov, N.E., Kupka, F., Ryabchikova, T.A., Weiss, W.W., & Jeffery, C.S. 1995, A&ASuppl., 112, 525

Plez, B., 1998, A&A, 337, 495

Plez, B. 1999, private communication.

Ruiz, M.T., Leggett, S.K., and Allard, F. 1997, ApJ, 491, L107

Saumon, D., Chabrier, G., and Van Horn, H.M. 1995, ApJS, 99, 713

Saumon, D., Geballe, T.R., Leggett, S.K., Marley, M.S., Freedman, R.S., Lodders, K., Fegley, B., and Sengupta, S.K. 2000, ApJ, 541, 374

Schultz, A.B. et al. 1998, ApJ, 492, L181

Strauss, M.A., et al. 1999, ApJ, 522, L61

Tokunaga, A.T., and Kobayashi, N. 1999, AJ, 117, 1010

Tsuji, T., Ohnaka, K., Aoki, W., and Nakajima, T. 1996, Astron. Astrophys. , 308, L29

Tsuji, T., Ohnaka, K., and Aoki, W. 1999, ApJ, 520, L119

Tsvetanov, Z.I., et al. 2000, ApJ, 531, L61

Zheng, C. and Borysow, A. 1995, Icarus, 113, 84

Table 1.   T/L Dwarfs highlighted in this Paper

Full Object Designation	Short Object Name	Spectral Subtype[a]	Reference
2MASSI J1507038-151648	2MASS-1507	L5	1
2MASSW J1632291+190441	2MASS-1632	L8	1
SDSSp J083717.22−000018.3	SDSS-0837	T1	2
SDSSp J125453.90−012247.4	SDSS-1254	T2	2
SDSSp J102109.69−030420.1	SDSS-1021	T3	2
2MASSI J0559191−140448	2MASS-0559	T5	3
SDSSp J162414.37+002915.6	SDSS-1624	T6	4
2MASSI J0937347+293142	2MASS-0937	T6p	5
SDSSp J134646.45−003150.4	SDSS-1346	T6	6
2MASSI J1237392+652615	2MASS-1237	T6.5	7
Gliese 229B	Gl 229B	T6.5	8
2MASSI J0727182+171001	2MASS-0727	T7	5
2MASSI J1217110−031113	2MASS-1217	T7.5	5
2MASSW J1457150-212148	Gl 570D	T8	9
2MASSI J0415195−093506	2MASS-0415	T8	5

References. — (1) Kirkpatrick et al. (1999); (2) Leggett et al. (2000); (3) Burgasser et al. (2000c); (4) Strauss et al. (1999); (5) Burgasser et al. (2001a); (6) Tsvetanov et al. (2000); (7) Burgasser et al. (1999); (8) Nakajima et al. (1995); (9) Burgasser et al. (2000a).

[a]Using the classification scheme of Kirkpatrick et al. (1999) for L dwarfs and Burgasser et al. (2001a) for T dwarfs.

Table 2.   Spectral Indices for T/L Dwarfs and Z = (0.3,1.0,2.0)×⊙
Models

$Dwarf/Model$	$i' - z'$[a]	$X97$[b]	$X23$[c]	$X98$[d]	$J - K$[e]	$X126.105$[f]
2MASS-1507 (L5,A[g])	2.16	0.68	0.07	−0.02	–	–
2MASS-1632 (L8,B)	2.88	1.10	0.17	0.14	–	–
SDSS-0837 (T1,C)	3.61	1.48	0.13	0.30	1.07	0.057
SDSS-1254 (T2,D)	4.08	1.58	0.11	0.37	0.98	0.120
SDSS-1021 (T3,E)	3.92	1.41	0.11	0.36	0.84	0.232
2MASS-0559 (T5,F)	4.32	1.69	0.13	0.38	0.17	0.188
SDSS-1624 (T6,G)	3.66	1.34	0.28	0.37	–	–
2MASS-0937 (T6p,I)	4.99	2.10	0.35	0.49	−0.57	0.127
SDSS-1346 (T6,H)	4.36	1.63	0.44	0.43	−0.33	0.230
2MASS-1237 (T6.5,K)	3.86	1.33	0.28	0.46	−0.40	0.083
Gl 229B (T6.5,J)	–	–	0.46	0.52	−0.16	−0.300
2MASS-0727 (T7,L)	4.06	1.76	0.29	0.34	−0.51	0.168
2MASS-1217 (T7.5,M)	3.83	2.35	0.34	0.37	−0.03	0.207
Gl 570D (T8,N)	4.38	1.97	0.53	0.41	−0.34	0.217
2MASS-0415 (T8,O)	4.01	1.82	0.35	0.40	−0.28	0.221

Z = ⊙

g = 10^5 cm s^{-2}:

1300 K	3.10	1.01	0.27	0.21	0.48	0.32
1200	3.63	1.29	0.43	0.33	0.31	0.14
1100	3.91	1.43	0.53	0.39	0.23	0.13
1000	4.14	1.52	0.62	0.40	0.09	0.17
900	4.38	1.64	0.72	0.42	−0.05	0.22
800	4.53	1.71	0.81	0.43	−0.29	0.27
700	4.63	1.78	0.91	0.45	−0.53	0.35
600	4.51	1.75	0.99	0.42	−0.92	0.45

g = $10^{5.5}$ cm s^{-2}:

1300 K	3.47	1.19	0.20	0.29	0.34	0.31

Table 2—Continued

$Dwarf/Model$	$i' - z'^{\mathrm{a}}$	$X97^{\mathrm{b}}$	$X23^{\mathrm{c}}$	$X98^{\mathrm{d}}$	$J - K^{\mathrm{e}}$	$X126.105^{\mathrm{f}}$
1200	3.83	1.35	0.28	0.34	0.18	0.34
1100	4.39	1.60	0.42	0.45	−0.09	0.16
1000	4.68	1.73	0.48	0.48	−0.24	0.20
900	4.74	1.76	0.52	0.47	−0.38	0.27
800	4.85	1.82	0.57	0.48	−0.69	0.35
700	4.70	1.78	0.63	0.47	−0.89	0.44
600	4.44	1.72	0.74	0.42	−1.26	0.50

No rainout:

| 900 K/5.$\odot$.norain | 3.20 | 1.23 | 0.83 | 0.31 | −0.12 | −0.15 |
| 900/5.5$\odot$.norain | 3.08 | 1.16 | 0.64 | 0.31 | −0.45 | −0.20 |

$\underline{Z = 0.3 \odot}$

$g = 10^5$ cm s^{-2}:

1300 K	3.19	1.00	0.17	0.21	0.11	0.32
1200	3.61	1.21	0.26	0.28	−0.09	0.25
1100	4.16	1.49	0.36	0.41	−0.35	0.14
1000	4.53	1.65	0.43	0.46	−0.48	0.13
900	4.89	1.80	0.47	0.49	−0.71	0.16
800	5.26	1.97	0.52	0.53	−1.01	0.19
700	5.23	1.97	0.56	0.54	−1.27	0.25
600	5.17	1.97	0.61	0.54	−1.82	0.30

$g = 10^{5.5}$ cm s^{-2}:

1300 K	3.56	1.17	0.13	0.28	−0.04	0.20
1200	4.15	1.46	0.18	0.39	−0.34	0.18
1100	4.59	1.64	0.22	0.46	−0.55	0.23

Table 2—Continued

$Dwarf/Model$	$i'-z'$[a]	X97[b]	X23[c]	X98[d]	$J-K$[e]	X126.105[f]
1000	4.89	1.77	0.26	0.50	−0.70	0.20
900	5.23	1.90	0.29	0.54	−0.90	0.18
800	5.44	2.00	0.32	0.59	−1.22	0.21
700	5.29	1.95	0.35	0.56	−1.51	0.26
600	5.11	1.90	0.40	0.54	−2.01	0.29

$\underline{Z = 2.0\,\odot}$

$g = 10^5$ cm s^{-2}:

1300 K	3.20	1.11	0.42	0.25	0.72	0.10
1200	3.44	1.20	0.48	0.26	0.58	0.21
1100	3.89	1.44	0.66	0.39	0.43	0.16
1000	4.13	1.55	0.77	0.39	0.29	0.11
900	4.12	1.55	0.84	0.38	0.30	0.18
800	4.29	1.65	0.97	0.39	0.17	0.26
700	4.37	1.71	1.12	0.40	−0.05	0.35
600	4.17	1.66	1.24	0.34	−0.36	0.45

$g = 10^{5.5}$ cm s^{-2}:

1300 K	3.69	1.30	0.35	0.36	0.42	0.12
1200	3.92	1.41	0.43	0.40	0.34	0.09
1100	4.06	1.48	0.49	0.41	0.25	0.13
1000	4.17	1.53	0.56	0.41	0.14	0.22
900	4.41	1.66	0.65	0.43	0.06	0.29
800	4.46	1.70	0.74	0.44	−0.12	0.38
700	4.39	1.69	0.82	0.42	−0.43	0.48
600	4.11	1.61	0.96	0.36	−0.73	0.56

[a]Sloan Digital Sky Survey (SDSS) AB band passes; 3631 Jy. zero-points

[b]X97 $= \log_{10}(\langle F_\lambda(0.90-0.91\,\mu\mathrm{m})\rangle/\langle F_\lambda(0.72-0.73\,\mu\mathrm{m})\rangle)$

[c]X23 $= \log_{10}(\langle F_\lambda(0.92-0.925\,\mu\mathrm{m})\rangle/\langle F_\lambda(0.928-0.945\,\mu\mathrm{m})\rangle)$

[d]X98 $= \log_{10}(\langle F_\lambda(0.90-0.91\,\mu\mathrm{m})\rangle/\langle F_\lambda(0.855-0.86\,\mu\mathrm{m})\rangle)$

[e]$J-K$ (Bessell); J zeropoint: 1600 Jy., K zeropoint: 655 Jy.

[f]X126.105 $= \log_{10}(F_\lambda(1.26\,\mu\mathrm{m})/F_\lambda(1.05\,\mu\mathrm{m}))$

Fig. 1.— The log (base ten) of the flux (F_ν) versus wavelength (λ) in microns from 0.6 μm to 1.0 μm for two late L dwarfs (2MASS-1507 and 2MASS-1632) and some representative T dwarfs for which optical data have recently been obtained (see Table 1 for references). All spectra have been normalized to be 1 milliJansky at 1.0 μm so that the relative flux levels are more easily compared. The objects are listed in the graph from early to late spectral subtype (indicated next to the object name). Due to the low signal-to-noise ratio shortward of 0.8 μm for the latest T dwarfs and the desire to more easily discriminate objects, boxcar smoothing of from 10 to 20 Å has been applied below 0.8 μm for 2MASS-1624, 2MASS-0937, and Gliese 570D. Note that the 2MASS-0559 (T5) (green) spectrum shortward of 0.9 μm is "redder" than that of SDSS-1624 (T6) (blue), despite the former's earlier spectral subtype.

Fig. 2.— The log (base ten) of the flux (F_ν) versus wavelength (λ) in microns from 0.6 μm to 1.0 μm for six additional T dwarfs. This figure is a continuation of Fig. 1 and on it the data have been similarly normalized. Furthermore, boxcar smoothing, as described in Fig. 1, has been applied to SDSS-1346, 2MASS-0727, 2MASS-1217, and 2MASS-0415. Both this figure and Fig. 1 include Gliese 229 B (in gold) to enable cross comparison. Since SDSS-1021 and SDSS-1254 are rather close on this figure, an arrow has been used distinguish SDSS-1021. Note that the relative flux level of SDSS-1021 (T3) is generally above (at both 0.73 μm and 0.83 μm) that of SDSS-1254, despite the former's later spectral subtype.

Fig. 3.— The log (base ten) of the absolute flux (F_ν) in milliJanskys versus wavelength (λ) in microns from 0.4 μm to 1.5 μm for self-consistent theoretical solar-metallicity (Anders and Grevesse 1989) models of brown-dwarf/T-dwarf spectra generated for this paper. These spectra have been deresolved to an $R(\lambda/\Delta\lambda)$ of 1000. The dashed blue lines are for a gravity of $10^{5.5}$ cm s^{-2} and the red lines are for a gravity of 10^5 cm s^{-2}. Shown are models from 600 K to 1300 K, in steps of 100 K. The higher lines are for models with the higher $T_{\rm eff}$s . Prominent are the Na D and K I resonance doublets at $\sim$5890 Å and $\sim$7700 Å, the water features around 0.93 μm, 1.15 μm, and 1.4 μm, the Cs I lines at 8523 Å and 8946 Å, the Li I line at 6708 Å(for which see §11), the Rb I lines at 7802 Å and 7949 Å, and the TiO and VO features near $\sim$0.45 μm and 0.9→1.05 μm (for the hottest models). No clouds (which would affect the detectability of the TiO/VO features, among others) are incorporated into these models. Note that the K I doublet at 1.2432/1.2522 μm is seen for $T_{\rm eff}$s at 700 K and above. FeH and CrH bands are not incorporated into this model set (the corresponding opacity data are being updated for future publication).

Fig. 4.— The same set of solar-metallicity theoretical models depicted in Fig. 3, but over a wavelength range from 0.6 μm to 1.0 μm and normalized at 1.0 μm to a universal value of 1.0 (as in Figs. 1 and 2). The dashed blue lines are for a gravity of $10^{5.5}$ cm s^{-2} and the red lines are for a gravity of 10^5 cm s^{-2}. This figure is meant to be compared with Figs. 1 and 2. The general reddening trend in the optical with decreasing $T_{\rm eff}$ (at a given gravity) reverses at lower effective temperatures. At higher gravities, this reversal occurs at higher $T_{\rm eff}$s (for a given metallicity). This effect is particularly noticeable around 0.75 μm. See text for a discussion.

Fig. 5.— Atmospheric profiles of the temperature (T, in K) versus the logarithm (base ten) of the pressure (in dynes cm^{-2}) for different metallicities and for T_{eff}s of 900 K (solid) and 1300 K (dashed, one dotted). A gravity of $10^{5.5}$ cm s^{-2} was used for the solid and dashed models, while the lower-gravity model at 1300 K and twice solar metallicity is depicted with a dotted line. Note that pressure is plotted upside down, with the lower pressures at the top. The 2.0×solar-metallicity models are blue, the solar-metallicity models are black, and the 0.3×solar-metallicity models are red. Lower-metallicity models have higher pressures at a given temperature and higher-T_{eff} models have lower pressures at a given temperature. Lower-gravity models have lower pressures at a given temperature, as a comparison between the blue dashed and dotted curves demonstrates. Temperature/pressure profiles help determine the character of the emergent spectrum.

Fig. 6.— The "τ_λ" temperature ($T_{2/3}$) in Kelvin versus the wavelength (λ) in microns for T_{eff}s of 700, 900, and 1300 K and gravities of $10^{5.5}$ cm s^{-2} (thick, blue) and 10^5 cm s^{-2} (red) for the solar-metallicity models shown in Fig. 3. $T_{2/3}$ is defined in this paper as the temperature level in the brown dwarf atmosphere at which the total optical depth is 2/3. Hence, it is a measure of the "decoupling" temperature at a given wavelength, or the wavelength-dependent depth to which one probes an atmosphere. Note that, very roughly, the wavelengths at the flux peaks (see Fig. 3) are where $T_{2/3}$ is highest. For instance, in the z' band ($\sim$1.05 μm), one is probing to $\sim$1500-1600 K for the 1100 K models and in the J band ($\sim$1.25 μm), one is probing to $\sim$1400-1500 K, for the same models. Note that below the Na D line at $\sim$5890 Å, $T_{2/3}$ is rising to between 1200 and 1600 K, while at the centers of the strong Na D and K I resonance doublets, $T_{2/3}$ is near 800 K. See the text for a discussion of the conceptual usefulness of $T_{2/3}$.

Fig. 7.— A comparison of the absolute fluxes (F_ν), in milliJanskys) of Gliese 229B (gold) and Gliese 570D (red) with representative solar-metallicity model spectra for wavelengths (λ) from 0.6 μm to 1.4 μm. Gliese 229B should be compared with the models at [950 K/$10^{5.5}$ cm s^{-2}] (upper black) and [780 K/$10^{4.5}$ cm s^{-2}] (green) and Gliese 570D should be compared with the model at [750 K/10^5 cm s^{-2}] (lower black). The gold bars near 0.65 μm denote the WFPC2 R band measurement of Gliese 229B of Golimowski et al. (1998). The fits are good, but, at the current precision, not unique.

Fig. 8.— The log (base ten) of the absolute flux (F_ν) in milliJanskys versus wavelength (λ) in microns from 0.4 μm to 1.5 μm for various T_{eff} = 900 K solar-metallicity models. The red line depicts the [900 K/10^5 cm s^{-2}] model and the solid blue line the [900 K/$10^{5.5}$ cm s^{-2}] model. The black line portrays a model with $g = 10^{5.5}$ cm s^{-2}, but using strict Lorentzian line profiles for the Na D and K I (7700 Å) lines, as well as no rainout for the Ti/V compounds (note the region around 0.45 μm). The dashed blue line is a [900 K/$10^{5.5}$ cm s^{-2}] model, but one that does not incorporate a prescription for the rainout of the silicates and the consequent survival of Na and K to lower temperatures and pressures in the atmosphere. For comparision, the spectrum of 2MASS-0559 (T5) is included in green and is the absolute flux spectrum under the assumption that its distance is 10 parsecs. The rainout and no-rainout models (solid blue versus dashed blue) are very different

shortward of 1.0 μm. Even for the low T_{eff} (900 K) models shown here, the no-rainout model can not even qualitatively reproduce the steeper spectral slope and lower bump between 0.65 μm and 0.75 μm seen generically in the optical/near-IR data (see Figs. 1 and 2), as exemplified here with the 2MASS-0559 (T5) spectrum. See text for discussion.

Fig. 9.— This is a plot of the log (base ten) of the flux (F_ν) in milliJanskys versus the wavelength (λ) in microns from 0.4 μm to 1.5 μm of model spectra at $T_{eff} = 900$ K and with a gravity of $10^{5.5}$ cm s^{-2} for metallicities at 0.3, 1.0, and 2.0 times solar (Anders and Grevesse 1989). Shortward of 0.9 μm, the lower-metallicity model is redder and the higher-metallicity model is bluer than the solar model. Furthermore, the lower-metallicity model has a more rounded Z band peak. Overall, the 1.0 and 2.0×solar models are very similar. However, there are metallicity differences shortward of 0.6 μm, as well as in the water troughs (particularly around 0.93 μm). The differences in the near-IR at H and K are more pronounced, with lower-metallicity models being generically more blue in $J - K$ and $H - K$. For instance, from 600 to 1300 K, the differences between the solar-metallicity and the 0.3×solar-metallicity models vary from 0.1 to 0.5 magnitudes in $J - K$.

Fig. 10.— Index X97 ($\log_{10}(F_\lambda(0.90 - 0.91\mu m)/F_\lambda(0.72 - 0.73\mu m))$) versus index X98 ($\log_{10}(F_\lambda(0.90 - 0.91\mu m)/F_\lambda(0.855 - 0.86\mu m))$) for a set of theoretical models and a subset of the observed T and late L dwarfs listed in Table 1. X97 is a measure of the relative fluxes at ∼0.9 μm and the bump between the K I resonance doublet at 7700 Å and the Na D line(s) (see Figs. 1, 2, 3, and 4). X98 is one measure of the spectral slope between (but not including) the K I doublet and the water feature at ∼0.93 μm. These indices are also given in Table 2. This and the following "pseudo" color-color diagrams help to quantify the behavior at "short" wavelengths of that part of a brown dwarf spectrum that is dominated by the resonance alkali metal lines. For the theory, the connected black dots and lines are for solar metallicity, those in gold are for 0.3×solar metallicity, and those in blue are for 2.0×solar metallicity. The dashed lines are for a gravity of 10^5 cm s^{-2} and the solid lines are for a higher gravity of $10^{5.5}$ cm s^{-2}. Each theory line connects models from 1300 K to 600 K, in steps of 100 K. Notice the hook in these lines are lower T_{eff}s, even though much of the higher T_{eff} behavior is monotonic. The basic trends and systematics can be gleaned at a glance, though extracting the specifics requires closer scrutiny. The single letters denote observed objects: the blue letters are the L dwarfs 2MASS-1507 (A) and 2MASS-1632 (B), the green letters are SDSS-0837 (C), SDSS-1254 (D), and SDSS-1021 (E), and the red letters are the later T dwarfs, 2MASS-0559 (F), SDSS-1624 (G), SDSS-1346 (H), 2MASS-0937 (I), Gl 229B (J, not shown here), 2MASS-1237 (K), 2MASS-0727 (L), 2MASS-1217 (M), Gl 570D (N), and 2MASS-0415 (O). They are in order of spectral subtype, as derived by Burgasser et al. (2001a) (see Table 2). Refer to the text for a general discussion of this and related Figures 11 through 13. Note that any error bars for the indices have been suppressed for clarity, but they are generally around 0.1 dex.

Fig. 11.— The same as Fig. 10, but for i′-z′ (Sloan) versus X98. The basic trends in the theory lines are clear. (See text for a discussion and Table 2 for a listing.) As stated in Fig. 10, error bars for the data points have been suppressed for clarity, but they are ∼0.1 dex for X98 and ∼0.2$^+$ mag

for i$'$-z$'$.

Fig. 12.— The same as Fig. 10, but for i$'$-z$'$ (Sloan) versus $J - K$ (Bessell). The use of the Bessell (Cousins) system in this plot is arbitrary and the quoted colors have been derived from the spectra themselves. As used, our $J - K$ (Bessell) value can be considered merely yet another index to gauge relative slopes and shapes. Note that fluxing and absolute calibration for the spectra of the depicted T dwarfs may have errors as high as 0.25 mag. In addition, note that the difference between the photometrically-derived (not used) and spectroscopically-derived magnitudes can at times be of a similar magnitude (Burgasser et al. 2001a). The theoretical and observed spectra have been treated equally in obtaining the numbers (see Table 2) for this plot. On this plot, H (SDSS-1346) and N (Gl 570D) are very close (see Table 2).

Fig. 13.— The same as Fig. 10, but for X98 versus X23 ($\log_{10}(F_\lambda(0.92 - 0.925\mu\mathrm{m})/F_\lambda(0.928 - 0.945\mu\mathrm{m}))$). Note that, unlike on Figs. 10 through 12, Gliese 229B (J, gold) is found on this plot. X23 is a measure of the relative depth of the water feature at $\sim$0.93 μm .

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